CATALYST AND PROCESS FOR THE PRODUCTION OF ACETIC ACID

The present invention relates to a process for the production of acetic acid and in particular, to a process for the production of acetic acid by carbonylation in the presence of an iridium catalyst and methyl iodide co-catalyst.

The production of acetic acid by the carbonylation of methanol in the presence of
5   an iridium catalyst is known and is described, for example in, EP-A-0643034 and EP-A-0752406.
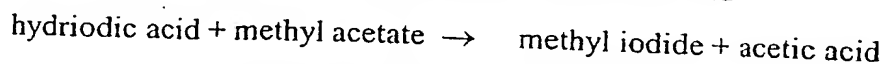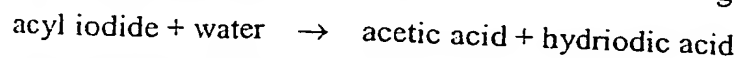
EP-A-0643034 describes a process for the production of acetic acid by carbonylation of methanol or a reactive derivative thereof which process comprises contacting methanol or a reactive derivative thereof with carbon monoxide in a liquid
10   reaction composition in a carbonylation reactor characterised in that the liquid composition comprises (a) acetic acid, (b) an iridium catalyst, (c) methyl iodide, (d) at least a finite quantity of water, (e) methyl acetate and (f) as promoter, at least one of ruthenium and osmium.

EP-A-0752406 describes a process for the production of acetic acid comprising (1)
15   continuously feeding methanol and/or a reactive derivative thereof and carbon monoxide to a carbonylation reactor which contains a liquid reaction composition comprising an iridium carbonylation catalyst, methyl iodide co-catalyst, a finite concentration of water, acetic acid, methyl acetate and at least one promoter; (2) contacting the methanol and/or reactive derivative thereof with the carbon monoxide in
20   the liquid reaction composition to produce acetic acid; and (3) recovering acetic acid from the liquid reaction composition characterised in that there is continuously maintained in the liquid reaction composition throughout the course of the reaction (a) water at a concentration of no greater than 6.5 % by weight, (b) methyl acetate at a

concentration in the range 1 to 35 % by weight and (c) methyl iodide at a concentration in the range 4 to 20 % by weight.

It has now been surprisingly found that by using a non-hydrohalogenoic acid in an iridium-catalysed carbonylation process for the production of acetic acid improved carbonylation rates may be achieved.

In the iridium-catalysed carbonylation of methanol (or reactive derivative thereof) hydriodic acid is generated and consumed via the following reaction mechanisms

acyl iodide + water $\rightarrow$ acetic acid + hydriodic acid

hydriodic acid + methyl acetate $\rightarrow$ methyl iodide + acetic acid

As the concentration of hydriodic acid is increased the rate of carbonylation is found to decrease. It is therefore surprising that the concentration of protons (H^+) in the carbonylation system can be increased without having a detrimental effect on the carbonylation rate.

Thus, according to the present invention there is provided a catalyst system for the production of acetic acid which catalyst system comprises an iridium carbonylation catalyst, methyl iodide co-catalyst, optionally at least one of ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and indium and at least one non-hydrohalogenoic acid promoter.

The present invention also provides a process for the production of acetic acid by reacting carbon monoxide with methanol and/or a reactive derivative thereof in a liquid reaction composition comprising methyl acetate, a finite concentration of water, acetic acid and a catalyst system comprising an iridium carbonylation catalyst, methyl iodide co-catalyst, optionally at least one of ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and indium and at least one non-hydrohalogenoic acid promoter.

The present invention further provides for the use of a catalyst system for the production of acetic acid which catalyst system comprises an iridium carbonylation catalyst, methyl iodide co-catalyst, optionally at least one of ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and indium and at least one non-hydrohalogenoic acid promoter.

The non-hydrohalogenoic acid for use in the process present invention may suitably be at least one of an oxoacid, a superacid and a heteropolyacid. Mixtures of non-hydrohalogenoic acids of the same or different type may be used such as mixtures

of at least two different oxoacids or at least two different superacids or at least two different heteropolyacids or a mixture of at least one oxoacid and/or at least one superacid and/or at least one heteropolyacid. It will be understood by the skilled person that an acid may be both of the oxoacid and a superacid type.

5   Oxoacids are compounds with X-OH groups of the type H_nXO_m wherein X is a non-metal or metal and n and m are integers. Examples of common oxoacids are H_3PO_4, H_2SO_4, HNO_3 and $HClO_4$

Suitable oxoacids for use in the process of the present invention include the oxoacids of the elements of Groups 13 to 17 of the Periodic Table.

10   Suitable oxoacids of the elements of Group 13 include the oxoacids of boron such as H_3BO_3. Group 14 oxoacids include those of germanium such as H_4GeO_4. Group 15 oxoacids include the oxoacids of nitrogen, phosphorus and arsenic. Suitable nitrogen-containing oxoacids include HNO_3 and HNO_2. Examples of phosphorus-containing oxoacids include H_3PO_4, H_3PO_3 and H_3PO_2. Examples of arsenic-containing oxoacids

15   . include H_3AsO_3. Group 16 oxoacids include the oxoacids of sulphur such as H_2SO_4, H_2SO_3, triflic acid, p-toluenesulphonic acid, selenium, for example H_2SeO_3 and H_2SeO_4 and tellurium such as H_6TeO_6. Group 17 oxoacids may be oxoacids of bromine, iodine and chlorine such as HBrO, HClO, H_5IO_6, $HClO_2$ and $HClO_4$.

Preferred oxoacids are H_2SO_4, HNO_3 and H_3PO_4 or mixtures thereof.

20   Acidity can be measured in a wide variety of solvents. Typically the acidity of a substance is measured in water and the hydrogen ion concentration generated by the substance therein is often given in terms of the pH scale. Solutions of a substance having a pH lower than 7.0 are acidic; those of higher pH are alkaline. However, the concepts of hydrogen ion concentration and pH are meaningful only for dilute aqueous

25   solutions of acids. Thus, a widely used means for determining acidity in other media and at high concentrations is the Hammett acidity function H_0. The acidity function, H_0, is defined as

$$H_0 = pK_{BH+} - \log [BH^+] / [B]$$

where [B] is   concentration of a weak base (indicator)

30          $[H^+]$ is   concentration of the conjugate acid of the weak base

pK_{BH+} is pK of indicator in water

The H_0 value of an acidic substance is measured using indicators that are weak

bases (B) such as o-nitroaniline or 2,4-dinitroaniline. The weak base is (partly) converted in the acidic substance to the conjugate acid of the base (BH^+). The value of $[BH^+]$ / $[B]$ is typically measured by spectrophotometric means. By using the known pK in water for the base, H_0 can then be calculated for the acidic substance.

5   Acidic substances with $-H_0$ values above about 12 are referred to as superacids. Superacids are upward of 10^6 times as strong as a 1 molar aqueous solution of a strong acid. Acids with a $-H_0$ of greater than 12.1 (measured as the pure acid), are suitable for use in the process of the present invention.

The superacids for use in the process of the present invention have non-
10   coordinating anions by which is meant that little or no covalent interaction between the anion and iridium.

Suitable superacids for use in the process of the present invention include acids which have the following anions BF_4^-, PF_6^-, $(CF_3SO_2)_2N^-$, $CBH_6Br_6^-$, $CF_3SO_3^-$, SbF_6^-, FSO_3^- or mixtures thereof.

15   Specific examples of suitable superacids include HBF_4, HPF_6, $(CF_3SO_2)_2NH$ and $HCBH_6Br_6$.

The term "heteropolyacid" as used herein and throughout the specification means the free acid and does not include the associated metal salts thereof. The heteropolyacid anion may comprise from two to eighteen oxygen-linked polyvalent
20   metal atoms, which are generally known as the "peripheral" atoms. These peripheral atoms surround one or more central atoms in a symmetrical manner. The peripheral atoms are usually one or more of molybdenum, tungsten, vanadium, niobium, tantalum and other metals. The central atoms are usually silicon or phosphorus but can comprise any one of a large variety of atoms from Groups I-
25   VIII in the Periodic Table of elements. These include, for instance, cupric ions; divalent beryllium, zinc, cobalt or nickel ions; trivalent boron, aluminium, gallium, iron, cerium, arsenic, antimony, phosphorus, bismuth, chromium or rhodium ions; tetravalent silicon, germanium, tin, titanium, zirconium, vanadium, sulphur, tellurium, manganese nickel, platinum, thorium, hafnium, cerium ions and other
30   rare earth ions; pentavalent phosphorus, arsenic, vanadium, antimony ions; hexavalent tellurium ions; and heptavalent iodine ions. Such heteropolyacids are also known as "polyoxoanions", "polyoxometallates" or "metal oxide clusters".

Heteropolyacids usually have a high molecular weight, for example, in the range

from 700-8500 and include dimeric complexes. They have a relatively high solubility in polar solvents such as water or other oxygenated solvents, especially if they are free acids. Suitably, the heteropolyacid may have molybdenum and/or tungsten as peripheral atoms. Specific examples of heteropolyacids that may be used in the process of the present invention include :

12-tungstophosphoric acid	-	$H_3[PW_{12}O_{40}].xH_2O$
12-molybdophosphoric acid	-	$H_3[PMo_{12}O_{40}].xH_2O$
12-tungstosilicic acid	-	$H_4[SiW_{12}O_{40}].xH_2O$
12-molybdosilicic acid	-	$H_4[SiMo_{12}O_{40}].xH_2O$

The non-hydrohalogenoic acid for use in the process of the present invention may be introduced directly into the reactor, together with or separately from a reactant feed stream. The non-hydrohalogenoic acid may be used in the form of an aqueous solution of the acid.

The amount of the non-hydrohalogenoic acid to be used in the process of the present invention should be sufficient to provide a promotional effect on the carbonylation rate. The exact amount will depend on the specific non-hydrohalogenoic used and, in particular, on the nature and concentration of the anion of the acid. Without wishing to be bound by any theory, it is believed that certain anions, such as those of oxoacids, may co-ordinate to the iridium metal, and thus, if the concentration of these oxoanions is too high, a detrimental effect of the carbonylation rate may ensue. However, if the anion is non-coordinating to the iridium metal, higher concentrations of the acid may be employed.

Suitably, the amount of a superacid which may be added to the liquid reaction composition is such that the molar ratio of the anion to iridium is in the range [greater than 0 to 2.5] : 1, preferably, in the range [greater than 0 to 1] : 1, especially, in the range [0.05 to 0.5] : 1.

Typically, the amount of oxoacid which may be added to the liquid reaction composition is such that the molar ratio of anion to iridium is in the range [greater than 0 to 0.4] : 1. Where the anion is SO_4^{2-}, NO_3^- or PO_4^{3-}, derived from sulphuric, nitric and phosphoric acids respectively, the molar ratio of anion to iridium is preferably in the range [greater than 0 to 0.4] : 1, suitably [greater than 0 to 0.35] : 1, such as in the range [0.05 to 0.3] : 1.

Suitably, the amount of a heteropolyacid which may be added to the liquid

reaction composition is such that the molar ratio of the anion to iridium is in the range [greater than 0 to 5] : 1, preferably, in the range [greater than 1 to 4] :1, especially, in the range [1.5 to 3.5] : 1.

The iridium catalyst in the liquid reaction composition may comprise any iridium-containing compound which is soluble in the liquid reaction composition. The iridium catalyst may be added to the liquid reaction composition in any suitable form which dissolves in the liquid reaction composition or is convertible to a soluble form. Preferably the iridium may be used as a chloride free compound such as acetates which are soluble in one or more of the liquid reaction composition components, for example water and/or acetic acid and so may be added to the reaction as solutions therein. Examples of suitable iridium-containing compounds which may be added to the liquid reaction composition include $IrCl_3$, IrI_3, $IrBr_3$, $[Ir(CO)_2I]_2$, $[Ir(CO)_2Cl]_2$, $[Ir(CO)_2Br]_2$, $[Ir(CO)_4I_2]^-H^+$, $[Ir(CO)_2Br_2]^-H^+$, $[Ir(CO)_2I_2]^-H^+$, $[Ir(CH_3)I_3(CO)_2]^-H^+$, $Ir_4(CO)_{12}$, $IrCl_3.4H_2O$, $IrBr_3.4H_2O$, $Ir_3(CO)_{12}$, iridium metal, Ir_2O_3, IrO_2, $Ir(acac)(CO)_2$, $Ir(acac)_3$, iridium acetate, $[Ir_3O(OAc)_6(H_2O)_3][OAc]$, and hexachloroiridic acid $H_2[IrCl_6]$, preferably, chloride-free complexes of iridium such as acetates, oxalates and acetoacetates.

Preferably, the concentration of the iridium catalyst in the liquid reaction composition is in the range 100 to 6000 ppm by weight of iridium.

Optionally, the liquid reaction composition may also comprise one or more of ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and indium, more preferably ruthenium and osmium. The ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and indium may be used in any suitable metal-containing compound which is soluble in the liquid reaction composition. The ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and indium may be added to the liquid reaction composition for the carbonylation reaction in any suitable form which dissolves in the liquid reaction composition or is convertible to soluble form.

Examples of suitable ruthenium-containing compounds which may be used as include ruthenium (III) chloride, ruthenium (III) chloride trihydrate, ruthenium (IV) chloride, ruthenium (III) bromide, ruthenium metal, ruthenium oxides, ruthenium (III) formate, $[Ru(CO)_3I_3]^-H^+$, $[Ru(CO)_2I_2]_n$, $[Ru(CO)_4I_2]$, $[Ru(CO)_3I_2]_2$,

tetra(aceto)chlororuthenium(II,III), ruthenium (III) acetate, ruthenium (III) propionate, ruthenium (III) butyrate, ruthenium pentacarbonyl, trirutheniumdodecacarbonyl and mixed ruthenium halocarbonyls such as dichlorotricarbonylruthenium (II) dimer, dibromotricarbonylruthenium (II) dimer, and other organoruthenium complexes such as tetrachlorobis (4-cymene)diruthenium(II), tetrachlorobis(benzene)diruthenium(II), dichloro(cycloocta-1,5diene) ruthenium (II) polymer and tris(acetylacetonate)ruthenium (III).

Examples of suitable osmium-containing compounds which may be used include osmium (III) chloride hydrate and anhydrous, osmium metal, osmium tetraoxide, triosmiumdodecacarbonyl, $[Os(CO)_4I_2]$, $[Os(CO)_3I_2]_2$, $[Os(CO)_3I_3]$-H+, pentachloro-μ-nitrodiosmium and mixed osmium halocarbonyls such as tricarbonyldichloroosmium (II) dimer and other organoosmium complexes.

Examples of suitable rhenium-containing compounds which may be used include $Re_2(CO)_{10}$, $Re(CO)_5Cl$, $Re(CO)_5Br$, $Re(CO)_5I$, $ReCl_3.xH_2O$, $[Re(CO)_4I]_2$, $Re(CO)_4I_2]^-$ H^+ and $ReCl_5.yH_2O$.

Examples of suitable cadmium-containing compounds which may be used include $Cd(OAc)_2$, CdI_2, $CdBr_2$, $CdCl_2$, $Cd(OH)_2$, and cadmium acetylacetonate.

Examples of suitable mercury-containing compounds which may be used include $Hg(OAc)_2$, HgI_2, $HgBr_2$, $HgCl_2$, Hg_2I_2, and Hg_2Cl_2.

Examples of suitable zinc-containing compounds which may be used include $Zn(OAc)_2$, $Zn(OH)_2$, ZnI_2, $ZnBr_2$, $ZnCl_2$, and zinc acetylacetonate.

Examples of suitable gallium-containing compounds which may be used include gallium acetylacetonate, gallium acetate, $GaCl_3$, $GaBr_3$, GaI_3, Ga_2Cl_4 and $Ga(OH)_3$.

Examples of suitable indium-containing compounds which may be used include indium acetylacetonate, indium acetate, $InCl_3$, $InBr_3$, InI_3, InI and $In(OH)_3$.

Examples of suitable tungsten-containing compounds which may be used include $W(CO)_6$, WCl_4, WCl_6, WBr_5, WI_2, C_9H_{12} $W(CO)_3$ and any tungsten chloro-, bromo- or iodo-carbonyl compound.

Where ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and/or indium is used, it is preferably present in an effective amount up to the limit of its solubility in the liquid reaction composition and/or any liquid process streams recycled to the carbonylation reactor from the acetic acid recovery stage. The

ruthenium, osmium, rhenium, zinc, gallium, tungsten, cadmium, mercury and/or indium
is suitably present in the liquid reaction composition at a molar ratio of metal to iridium
of [1 to 15]:1, preferably [2 to 10]:1, more preferably [4 to 10]:1. A suitable ruthenium,
osmium or rhenium, zinc, gallium, tungsten, cadmium, mercury and/or indium

5   concentration is less than 8000 ppm, such as 400 to 7000 ppm.

Preferably, the iridium- and any ruthenium, osmium, rhenium, zinc, gallium,
tungsten, cadmium, mercury and indium -containing compounds are free of impurities
which provide or generate in situ ionic iodides which may inhibit the reaction, for
example, alkali or alkaline earth metal or other metal salts.

10   Ionic contaminants such as, for example, (a) corrosion metals, particularly
nickel, iron and chromium and (b) phosphines or nitrogen containing compounds or
ligands which may quaternise in situ; should be kept to a minimum in the liquid reaction
composition as these will have an adverse effect on the reaction by generating I^- in the
liquid reaction composition which has an adverse effect on the reaction rate. Some

15   corrosion metal contaminants such as for example, molybdenum have been found to be
less susceptible to the generation of I^-. Corrosion metals which have an adverse affect
on the reaction rate may be minimised by using suitable corrosion resistant materials of
construction. Similarly, contaminants such as alkali metal iodides, for example lithium
iodide, should be kept to a minimum. Corrosion metal and other ionic impurities may

20   be reduced by the use of a suitable ion exchange resin bed to treat the reaction
composition, or preferably a catalyst recycle stream. Such a process is described in US
4007130. Preferably, ionic contaminants are kept below a concentration at which they
would generate 500 ppm I^-, preferably less than 250 ppm I^- in the liquid reaction
composition.

25   In the process of the present invention, the concentration of methyl iodide co-
catalyst in the liquid reaction composition is preferably in the range 5 to 16 % by
weight.

In the process of the present invention, suitable reactive derivatives of methanol
include methyl acetate, dimethyl ether and methyl iodide. A mixture of methanol and

30   reactive derivatives thereof may be used as reactants in the process of the present
invention. Water is required as co-reactant for ether or ester reactants. Preferably,
methanol and/or methyl acetate are used as reactants.

At least some of the methanol and/or reactive derivative thereof will be

converted to, and hence present as, methyl acetate in the liquid reaction composition by reaction with the carboxylic acid product or solvent. Preferably, the concentration of methyl acetate in the liquid reaction composition is in the range 1 to 70% by weight, more preferably 2 to 50% by weight, most preferably 3 to 35% by weight

5   Water may be formed in-situ in the liquid reaction composition, for example, by the esterification reaction between methanol reactant and acetic acid product. Small amounts of water may also be produced by hydrogenation of methanol to produce methane and water. Water may be introduced to the carbonylation reactor together with or separately from other components of the liquid reaction composition. Water may be

10   separated from other components of reaction composition withdrawn from the reactor and may be recycled in controlled amounts to maintain the required concentration of water in the liquid reaction composition. The water concentration in the liquid reaction composition is suitably in the range 1-15 wt%, such as 1-10 wt%, preferably in the range 1-6.5 wt%.

15   The carbon monoxide reactant may be essentially pure or may contain inert impurities such as carbon dioxide, methane, nitrogen, noble gases, water and C_1 to C_4 paraffinic hydrocarbons. The presence of hydrogen in the carbon monoxide feed and generated in-situ by the water gas shift reaction is preferably kept low as its presence may result in the formation of hydrogenation products. Thus, the amount of hydrogen

20   in the carbon monoxide reactant is preferably less than 1 mol %, more preferably less than 0.5 mol % and yet more preferably less than 0.3 mol % and/or the partial pressure of hydrogen in the carbonylation reactor is preferably less than 1×10^5 N/m^2 partial pressure, more preferably less than 5×10^4 N/m^2 and yet more preferably less than 3×10^4 N/m^2. The partial pressure of carbon monoxide in the reactor is suitably in the

25   range 1×10^5 N/m^2 to 7×10^6 N/m^2, preferably 1×10^5 N/m^2 to 3.5×10^6 N/m^2, more preferably 1×10^5 N/m^2 to 1.5×10^6 N/m^2.

The total pressure of the carbonylation reaction is suitably in the range 1×10^6 N/m^2 to 2×10^7 N/m^2, preferably 1.5×10^6 N/m^2 to 1×10^7 N/m^2, more preferably 1.5×10^6 N/m^2 to 5×10^6 N/m^2.

30   The temperature of the carbonylation reaction is suitably in the range 100 to 300 °C, preferably in the range 150 to 220 °C.

The process of the present invention may be performed as a batch or as a continuous process, but is preferably performed as a continuous process.

The acetic acid product may be recovered from the liquid reaction composition by withdrawing vapour and/or liquid from the carbonylation reactor and recovering acetic acid from the withdrawn material. Preferably, acetic acid is recovered from the liquid reaction composition by continuously withdrawing liquid reaction composition from the

5   carbonylation reactor and recovering acetic acid from the withdrawn liquid reaction composition by one or more flash and/or fractional distillation stages in which the acetic acid is separated from the other components of the liquid reaction composition such as iridium catalyst, methyl iodide co-catalyst, methyl acetate, unreacted methanol, water and acetic acid solvent which may be recycled to the reactor to maintain their

10   concentrations in the liquid reaction composition. To maintain stability of the iridium catalyst during the acetic acid product recovery stage, water in process streams containing iridium carbonylation catalyst for recycle to the carbonylation reactor should be maintained at a concentration of at least 0.5 % by weight.

The process of the present invention may be performed a using carbonylation

15   reaction conditions known in the art, for example as described in EP-A-0786447, EP-A-0643034, EP-A-0752406 and EP-A-0749948, the contents of which are hereby incorporated by reference.

The invention will now be illustrated by way of example only and with reference to the following examples:

20   **General Reaction Method**

All experiments were performed in a 300 cm^3 zirconium autoclave equipped with a stirrer, liquid injection facility, ballast vessel and gas feed lines. Ruthenium acetate solution (when used, 5.08 wt% ruthenium metal, 71.3 wt% acetic acid and 17.8 wt% water), an aqueous solution of a non-hydrohalogenoic acid (when used) and part of the

25   acetic acid charge (10 g) were weighed into the autoclave base. The head of the autoclave was placed on the base and sealed before transferring the assembled unit to a blast cell. An electrical radiant heater and thermocouple were placed on the autoclave assembly before connecting to the gas and liquid feed lines, water cooling hoses and overhead stirrer. The gas and liquid feed inlet valves were opened and the assembly

30   pressure tested with nitrogen (32 N/m^2). The unit was flushed with nitrogen (1 x 20 N/m^2 pressure and vent cycle) followed by carbon monoxide (3 x 5 bar g pressure and vent cycles). The autoclave was opened to vent. Methyl iodide (13.33 g) followed by a mixture of water (approximately 13.15 g), acetic acid (approximately 42.66 g) and

methyl acetate (approximately 48.0 g) was added *via* a funnel before the autoclave was resealed. 6.3g iridium acetate solution (5.25 wt% iridium metal, 71.9 wt% acetic acid and 18.0 wt% water) was placed into the catalyst injector and washed in with the remaining acetic acid (approximately 8.7 g). Reactor charge compositions were

5   adjusted so the water, methyl iodide, methyl acetate and acetic acid levels were identical after catalyst injection for each reaction. The autoclave stirrer was switched on (1500 rpm) before pressurising with carbon monoxide (8 N/m^2). The assembly was heated to reaction temperature (190 °C). Once the temperature had stabilised the pressure in the autoclave was adjusted to the desired initial pressure as was the catalyst injector. The

10   ballast vessel was charged with carbon monoxide before injecting the catalyst solution with an over-pressure of carbon monoxide to bring the autoclave pressure to 28 bar g. After injection the autoclave pressure was kept constant at 28 N/m^2 by feeding carbon monoxide from the ballast vessel on demand. The temperature in the autoclave was kept constant by controlling the flow of cooling water. The reaction rate was monitored

15   by the drop in carbon monoxide pressure from the ballast vessel which was initially pressurised to approximately N/m^2 . On completion of the run the ballast vessel was isolated, the heater switched off and the autoclave cooled to below 30 °C. Once below 30 °C a gas sample could be taken from the head-space, if desired, before removing the autoclave from the blast cell and discharging. Liquid components were analysed by.

20   known, established gas chromatography methods. Detected components were quantified by integration of the component peaks relative to an external standard and expressed as parts per million (ppm) by mass. The major component in each batch carbonylation was acetic acid.

       The rate of gas uptake at a certain point in a reaction run was used to calculate the

25   carbonylation rate, as number of moles of reactant consumed per litre of cold degassed reactor composition per hour ($mol.dm^{-3}.hr^{-1}$) at a particular reactor composition (total reactor composition based on a cold degassed volume).

       Methyl acetate concentration was calculated during the course of the reaction from the starting composition, assuming that one mole of methyl acetate was consumed from

30   every mole of carbon monoxide that was consumed. No allowance was made for the organic components in the autoclave headspace.

Examples

Experiment A

A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (55.63 g), ruthenium acetate solution (6.87 g), water (13.16 g) and methyl iodide (13.33 g). The catalyst charge consisted of an iridium solution (6.30 g) with acetic acid (5.73 g). The ratio of iridium to ruthenium was 1:2. The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 1.

Example 1

Experiment A was repeated except that the autoclave was also charged with 98% H_2SO_4 solution (0.0172 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 1.

Experiment 2

Experiment A was repeated except that the autoclave was also charged with 98% H_2SO_4 solution (0.08g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 1.

Experiment 3

Experiment A was repeated except that the autoclave was also charged with 98% H_2SO_4 solution (0.345 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 1.

Table 1

Example/Experiment	Oxoacid	Ir/Ru/Oxoacid Molar Ratio	Rate at 12% MeOAc $(mol.dm^{-3}.hr^{-1})$
A	None	1:2:0	18.3
1	H_2SO_4	1:2:0.1	20.2
2	H_2SO_4	1:2:0.5	17.8
3	H_2SO_4	1:2:2	8.8

From an inspection of Table 1, it can be seen that the presence of a non-hydrohalogenoic acid (sulphuric acid) in a molar ratio of sulphate ions to iridium in a promotional amount provides an increased carbonylation rate compared to Experiments in which no non-hydrohalogenoic acid was present or where a high concentration of sulphate anion was present.

Experiment B

A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (57.58 g), water (14.37 g) and methyl iodide (13.33 g). The catalyst charge consisted of an iridium solution (6.30 g) with acetic acid (8.70 g). The

rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 2.

Experiment 4

Experiment B was repeated except that the autoclave was also charged with 85% H_3PO_4

5   solution (0.034 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 2.

Table 2

Example/Experiment	Oxoacid	Ir/Oxoacid Molar Ratio	Rate at 12% MeOAc ($mol.dm^{-3}.hr^{-1}$)
B	None	1 : 0	8.5
4	H_3PO_4	1 : 0.17	10.2

From an inspection of Table 1, it can be seen that the presence of orthophosphoric acid

10   provides an increased carbonylation rate compared to Experiment B in which no non-hydrohalogenoic acid was present.

Experiment C

A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (55.63 g), ruthenium acetate solution (6.87 g), water (13.16 g) and

15   methyl iodide (13.33 g). The catalyst charge consisted of an iridium solution (6.30 g) with acetic acid (5.73 g). The ratio of iridium to ruthenium was 1:2. The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Experiment D

20   A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (42.83 g), ruthenium acetate solution (20.54 g), water (10.71 g) and methyl iodide (13.33 g). The catalyst solution consisted of an iridium solution (6.30 g) with acetic acid (8.70 g). The ratio of iridium to ruthenium was 1:6. The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in

25   Table 3.

Experiment E

A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (42.83 g), water (10.71 g) and methyl iodide (13.33 g). The catalyst solution consisted of an iridium solution (6.30 g) with acetic acid (8.70 g). The

30   rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Example 5

Experiment C was repeated except that the autoclave was also charged with 60% HPF_6 solution (0.027 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

5   **Example 6**

Experiment C was repeated except that the autoclave was also charged with 60% HPF_6 solution (0.042 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Example 7

10   Experiment C was repeated except that the autoclave was also charged with 60% HPF_6 solution (0.084 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Example 8

Experiment C was repeated except that the autoclave was also charged with 60% HPF_6

15   solution (0.43g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Example 9

Experiment C was repeated except that the autoclave was also charged with 60% HPF_6 solution (0.9 g). The rate of reaction at a calculated reactor composition of 12% w/w

20   methyl acetate is shown in Table 3.

Example 10

Experiment C was repeated except that the autoclave was also charged with 48% HBF_4 solution (0.17 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

25   **Example 11**

Experiment D was repeated except that the autoclave was also charged with 60% HPF_6 solution (0.05 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Example 12

30   Experiment E was repeated except that the autoclave was also charged with 48% HPF_6 solution (0.17 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Example 13

Experiment E was repeated except that the autoclave was also charged with (CF$_3$SO$_2$)$_2$NH (0.24g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 3.

Table 3

Experiment	Acid	Ir/Ru/Acid Molar Ratio	Rate at 12% MeOAc (mol.dm^{-3}.hr^{-1})
C	None	1 : 2 : 0	18.3
5	HPF$_6$	1 : 2 : 0.1	20.3
6	HPF$_6$	1 : 2 : 0.1	20.3
7	HPF$_6$	1 : 2 : 0.2	19.2
8	HPF$_6$	1 : 2 : 1.0	19.8
9	HPF$_6$	1 : 2 : 2.2	19.8
10	HBF$_4$	1 : 2 : 0.5	20.8
D	None	1 : 6 : 0.0	27.3
11	HPF$_6$	1 : 6 : 0.1	29.1
E	None	1 : 0 : 0	8.1
12	HBF$_4$	1 : 0 : 0.5	10.5
13	(CF$_3$SO$_2$)$_2$NH	1 : 0 : 0.5	11.2

From an inspection of Table 3, it can clearly be seen from a comparison of Experiments C and D (where no non-hydrohalogenoic acid was present) with Examples 5 to 9 and 11 (where hexafluorophosphoric acid was used) that an increase in carbonylation rate was achieved in Examples 5 to 9 and 11.

A comparison of Experiment C with Example 10 (where tetrafluoroboric acid was present) shows that the addition of an acid according to the present invention provides an increase in carbonylation rate similar to that observed in Examples 5 to 9.

A comparison of Experiment E with Examples 12 and 13 shows that the addition of acids according to the present invention (tetrafluoroboric acid; (CF$_3$SO$_2$)$_2$NH) provide an increase in carbonylation rate in the absence of a ruthenium promoter.

Experiment F

A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (57.58 g), water (14.37 g) and methyl iodide (13.33 g). The catalyst solution consisted of an iridium solution (6.60 g) with acetic acid (8.70 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

Example 14

Experiment F was repeated except that the autoclave was also charged with

$H_3[PW_{12}O_{40}].xH_2O$ solid (5.835 g) and a reduced amount of acetic acid (53.38g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

Example 15

5   Experiment F was repeated except that the autoclave was also charged with $H_3[PW_{12}O_{40}].xH_2O$ solid (11.68 g) and a reduced amount of acetic acid (47.31g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

Example 16

10   Experiment F was repeated except that the autoclave was also charged with $H_3[PW_{12}O_{40}].xH_2O$ solid (17.47 g) and a reduced amount of acetic acid (41.4g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

Example 17

15   Experiment F was repeated except that the autoclave was also charged with $H_4[SiW_{12}O_{40}].xH_2O$ solid (5.84 g) and a reduced amount of acetic acid (53.38g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

Example 18

20   Experiment F was repeated except that the autoclave was also charged with $H_4[SiW_{12}O_{40}].xH_2O$ solid (11.72g) and a reduced amount of acetic acid (47.38g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

Table 4

Example/Experiment	HeteroPolyAcid (HPA)	Ir/HPA anion Molar Ratio	Rate at 12% MeOAc $(mol.dm^{-3}.hr^{-1})$
F	None	1 : 0	9.8
14	$H_3[PW_{12}O_{40}].xH_2O$	1 : 1	13.9
15	$H_3[PW_{12}O_{40}].xH_2O$	1 : 2	16.3
16	$H_3[PW_{12}O_{40}].xH_2O$	1 : 3	16.7
17	$H_4[SiW_{12}O_{40}].xH_2O$	1 : 1	12.4
18	$H_4[SiW_{12}O_{40}].xH_2O$	1 : 2	14.2

25

From Table 4 it can be seen that the presence of a heteropolyacid in Examples 14-18 provides an increased carbonylation rate compared to Experiment F where no heteropolyacid is present.

Experiment G

5   A baseline experiment was performed with the autoclave charged with methyl acetate (48.0 g), acetic acid (52.64 g), water (13.16 g), methyl iodide (13.33 g) and ruthenium solution (6.87 g). The catalyst solution consisted of an iridium solution (6.30 g) with acetic acid (8.70 g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 5.

10   **Example 19**

Experiment G was repeated except that the autoclave was also charged with $H_3[PW_{12}O_{40}].xH_2O$ solid (11.67g), ruthenium acetate (6.87g) and a reduced amount of acetic acid (32.53g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

15   **Example 20**

Experiment G was repeated except that the autoclave was also charged with $H_3[PW_{12}O_{40}].xH_2O$ solid (5.95g), indium acetate (0.534g) and a reduced amount of acetic acid (41.4g). The rate of reaction at a calculated reactor composition of 12% w/w methyl acetate is shown in Table 4.

20   **Table 5**

Example/Experiment	Promoter Metal (M)	HetroPolyAcid (HPA)	Ir/M/HPA anion Molar Ratio	Rate at 12% MeOAc $(mol.dm^{-3}.hr^{-1})$
G	Ruthenium	None	1 : 2 : 0	21.0
19	Ruthenium	$H_3[PW_{12}O_{40}].xH_2O$	1 : 2 : 2	25.9
20	Indium	$H_3[PW_{12}O_{40}].xH_2O$	1 : 1 : 1	15.5

From a comparison of Experiment G and Example 19 in Table 5 and also from a comparison of the results of Example 14 with Example 20 it can be seen that an increase in carbonylation rate can be achieved by the use of both a metal promoter and a
25   heteropolyacid compared to the rate obtainable by the use of a metal promoter alone.